Hydromagnetic Whistlers[1]

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Abstract. Hydromagnetic emissions consisting of a series of overlapping wavetrains of rising frequency are explained by hydromagnetic waves of anisotropic mode propagating along the field-aligned paths in the magnetosphere. The rising frequency of emission is attributed to the dispersive nature of the velocity of waves; the repetitive period of wavetrains is associated with the transit time of the wave packet bouncing between geomagnetic conjugate points along the line of force. It is suggested that an initiating wave is triggered by spontaneously injected high energy particles of superluminal motion and that the wave is subsequently amplified by plasma beams through the mechanism of cyclotron instabilities.

Introduction. In recent years interest in micropulsations in the geomagnetic field has been increasing, since there may be surface manifestations of hydromagnetic waves existing in the magnetosphere [*Dungey,* 1955; *Kato and Akasofu,* 1956; *Obayashi and Jacobs,* 1958; *Sugiura,* 1961]. Geomagnetic micropulsations are small oscillations in the periods ranging from 0.1 to 1000 sec appearing either as regular oscillations or irregular bursts. In particular, regular micropulsations in the period range about 0.2–5 sec, which belong in the category Pc 1 defined by the Commission 4 of IAGA, are of special interest. In earlier papers, they were often referred to as pearl-type micropulsations in which a sequence of discrete wave packets appears with regular intervals of a few minutes [*Benioff,* 1960; *Troitskaya,* 1961; *Saito,* 1962]. The frequency-time displays, sonagrams, of such pearl-type micropulsations reveal an interesting structure of emissions consisting of a series of overlapping wavetrains of rising frequency. This effect was first reported by *Tepley and Wentworth* [1962]. Independent observations of the effect were also obtained by *Gendrin and Stefant* [1962] and by *Mainstone and McNicol* [1962].

As is shown in Figure 1, the frequency band of emission lies around 1 cps, and the fine emission structure includes a number of repetitive wavetrains of rapidly rising frequency displaying a fan-shaped structure. Such emissions with a clear fine structure are usually found during magnetically quiet periods, and this structure seems to be destroyed during disturbed periods, being accompanied by the more rapidly rising tone of irregular structure emission [*Tepley,* 1964*a, b*]. It has been recognized that emissions of higher center frequency (0.5 to 1.5 cps) appear in the middle latitudes with shorter repetition periods of less than a few minutes, whereas the lower frequency ones (0.1 to 0.5 cps) are found in the auroral zone with their repetition periods from 2 to 5 minutes [*Heacock and Hessler,* 1962; *Campbell,* 1963]. A falling frequency fine structure is also occasionally observed.

Tepley [1961] has pointed out that those micropulsations are likely due to the effect of hydromagnetic waves of outer atmospheric origin, and he introduced the name 'hydromagnetic (hm) emissions.' In the present paper, this descriptive term is used for the phenomenon. However, this should not be confused with sudden bursts of hydromagnetic emissions, a spontaneous rapid enhancement of noise emissions spreading over the very wide frequency range. These bursts are closely related to energetic particle precipitations in high latitudes, enhanced ionospheric absorptions, and auroral X-ray bursts, and they are likely to be of ionospheric origin [*Campbell and Matsushita,* 1962; *Wentworth and Tepley,* 1962].

Theories have been proposed that hm emis-

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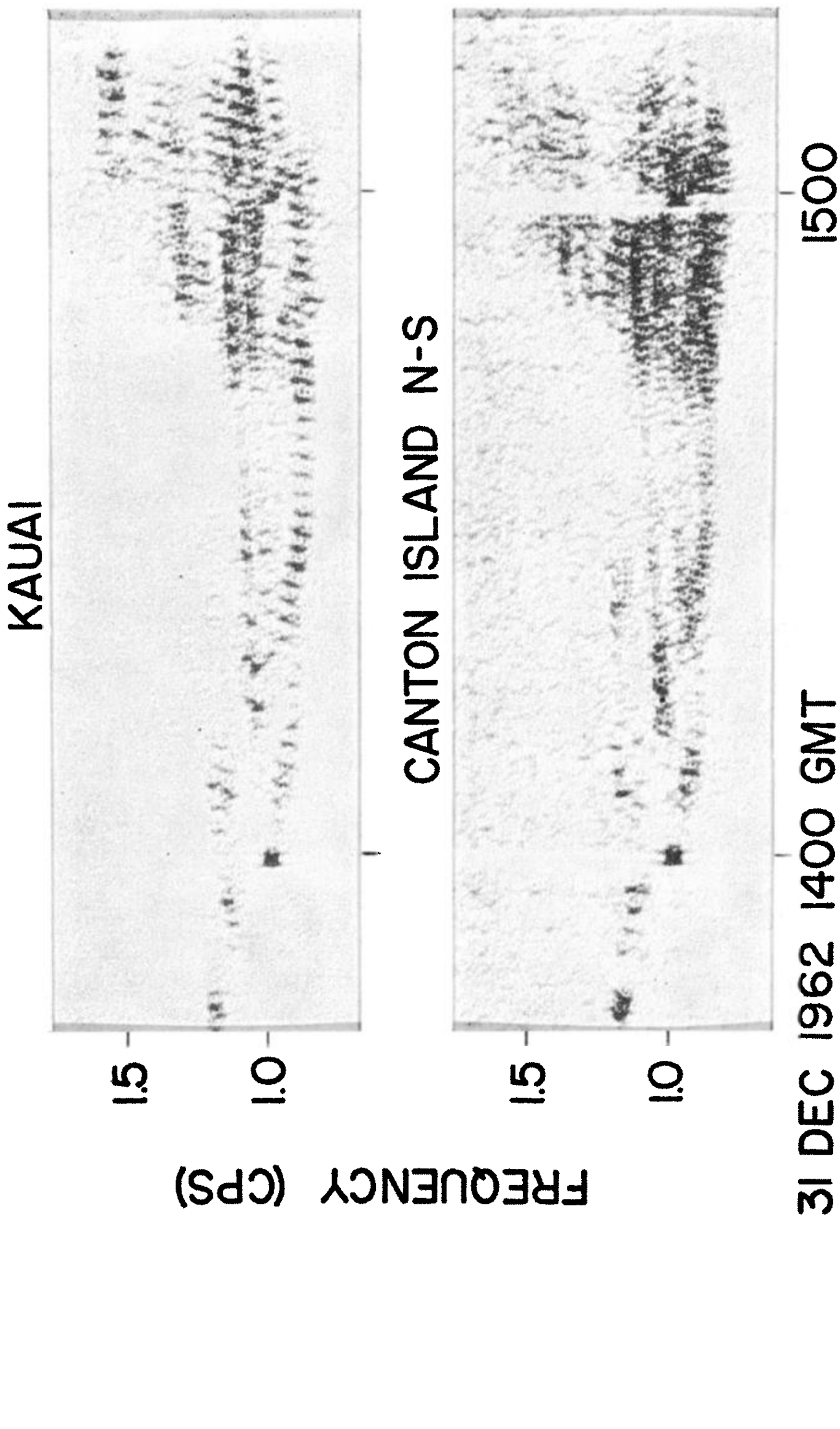

Fig. 1. Frequency-time displays of hydromagnetic emissions consisting of a fine structure of repetitive rising tone wavetrains. Note falling tones at 1420–1430 in Kauai record and double structure in Canton Island record [after *Tepley*, 1964*a*].

sions are produced by bunches of energetic charged particles oscillating along the geomagnetic field lines. *Wentworth and Tepley* [1962] postulated a fast electron bunch model in which hm emissions are attributed to the diamagnetism of an electron bunch, the emission frequency being associated with the bounce period of electrons between the geomagnetic conjugate mirror points. They suggested that the rising frequency fine structure may be associated with electron acceleration, though no explanation is given for the repetitive occurrence of emissions. A fast proton bunch model has been proposed by *Gendrin* [1963]. The theory is similar to that of the fast electron bunch in giving the emission frequency as the bounce period of particles. The fine structure periodicity is associated with the longitudinal drift period (orbiting period) of proton bunches around the earth. The rising frequency is explained by a latitude spread in the bunch at the time of the particle injection. In contrast to the above models, *Jacobs and Watanabe* [1963] postulated slow proton bunches bouncing along the geomagnetic field lines. Slow proton bunches excite resonant oscillations in the lower magnetosphere. The structure periodicity is associated with the proton bounce period, while the rising frequency is attributed to a latitude variation of the characteristic resonance frequency in the lower magnetosphere.

Because of the availability now of more observational evidence about hm emissions, it is apparent that these models present serious difficulties. Among several new facts discovered, the following are very important to the evaluation of the theory [*Tepley*, 1964*a*, *b*].

1. Hydromagnetic emissions occur simultaneously at widely spaced areas with the same period and regular repetitions, except for the signal amplitude, which decreases at lower latitudes.

2. It is found that there is a 180° phase shift between events which are observed simultaneously at stations in opposite hemispheres; i.e., the hm emissions are received alternately in the northern and southern hemispheres with the regular repetitive period.

3. Occasionally, a harmonic in the fine structure repetitive frequency (structure doubling) is observed near the equatorial stations. This can be interpreted in terms of a superposition of waves from opposite hemispheres, which are apparently propagated across the equator.

4. A diurnal variation seems to exist, which strongly supports a daytime maximum at all latitudes [*Wentworth*, 1964]. In the auroral zone they occur as frequently as in one quarter of the days of the year in groups of one to four days.

Of particular interest is the phase reversal in the opposite hemispheres. Since the model of fast particle bunches postulates that both electrons and protons oscillate very rapidly between conjugate points, the interhemisphere phase shift must be negligibly small. Therefore the model is not compatible with the observed result. In this respect, the slow proton bunch model may be the only one which could survive. However, this model predicts that the emission frequency should increase with geomagnetic latitude, which seems to be in conflict with the observed latitude variation.

In the present report an alternative theory is suggested: the sequence of emission structure is interpreted in terms of wave dispersion in the propagation of a hydromagnetic wave packet guided along the geomagnetic field line. *Jacobs and Watanabe* [1964] have also attempted to develop this line of thought. In this interpretation, hm emissions are produced in a manner similar to atmospheric whistler trains, and it may be appropriate to call them 'hydromagnetic whistlers.'

A theory of hydromagnetic whistlers is here developed, and some discussion is given on the production mechanism of emissions due to the interaction between particles and waves in the magnetosphere.

Hydromagnetic wave propagation in the magnetosphere. In an ionized plasma embedded in a magnetic field, three kinds of hydromagnetic waves exist in the range below the ion gyrofrequency: a pure Alfvén wave and two modes of magnetosonic waves. For the gas in which the magnetic energy density is much greater than the kinetic energy density of an ambient plasma, only two modes, the pure Alfvén wave and modified Alfvén wave, are important. The phase velocities of two waves propagating parallel to the magnetic field B are given, approximately, by

$$V = V_A(1 \pm \omega/\Omega_i)^{1/2} \tag{1}$$

where $V_A = B/(4\pi nM)^{1/2}$, the Alfvén velocity, ω = the wave angular-frequency, $\Omega_i/2\pi$ = the ion gyrofrequency, and the plus and minus signs stand for the fast-wave mode (modified Alfvén wave) and the slow-wave mode (pure Alfvén wave), respectively. The fast wave is propagated at higher velocities and higher frequencies, and this is the wave in which atmospheric whistlers are propagated in the VLF range. The fast wave has right-handed polarization and an upper frequency end at the electron gyrofrequency. For the slow wave, the velocity decreases as the frequency increases. This wave has left-handed polarization, and it becomes evanescent beyond the ion gyrofrequency. The phase velocity profile of waves in the entire frequency range is shown in Figure 2, which is typical in the magnetosphere. It has been shown that in the hydromagnetic wave range ($\omega^2 \ll \Omega_e\Omega_i$) the slow wave is highly anisotropic, i.e., the wave energy tends to be confined to a narrow cone along the magnetic field line, whereas the fast wave is more or less isotropic, being spread out in all directions [*Jacobs and Watanabe,* 1964].

Therefore a hydromagnetic wave of the anisotropic mode (the slow wave) excited in the magnetosphere will be guided along the geomagnetic field line (the fast wave is guided to a lesser extent until it reaches the frequency range $\omega^2 \gg \Omega_e\Omega_i$). Since the wave velocity shows a dispersive nature with frequency, the waves traversing the geomagnetic line of force between conjugate points will be observed as a time sequence of changing tones. Somewhat schematic frequency versus transit-time curves for wave packets traveling along the field line originating at the geomagnetic latitude 60° are illustrated in Figure 3. A familiar whistler curve appears in the VLF range, and two extremely delayed waves are shown in the hydromagnetic range. (The nature of the transition from the whistler to hydromagnetic regions shown in this diagram holds only for a plasma consisting of protons and electrons. The existence of other ionic constituents will introduce a considerable complication, giving rise to some cutoffs at the lower end of whistler waves [Smith and Brice, private communication, 1964].)

A rigorous computation of the frequency-time curves of hydromagnetic whistlers has been carried out as follows: The transit time (double-hop propagation time) along the geomagnetic field line is defined by

$$\tau = \int ds/V_g \qquad (2)$$

The group velocity V_g is

$$V_g = V_A\left(1 \pm \frac{\omega}{\Omega_i}\right)^{3/2}\left(1 \pm \frac{\omega}{2\Omega_i}\right)^{-1} \qquad (3)$$

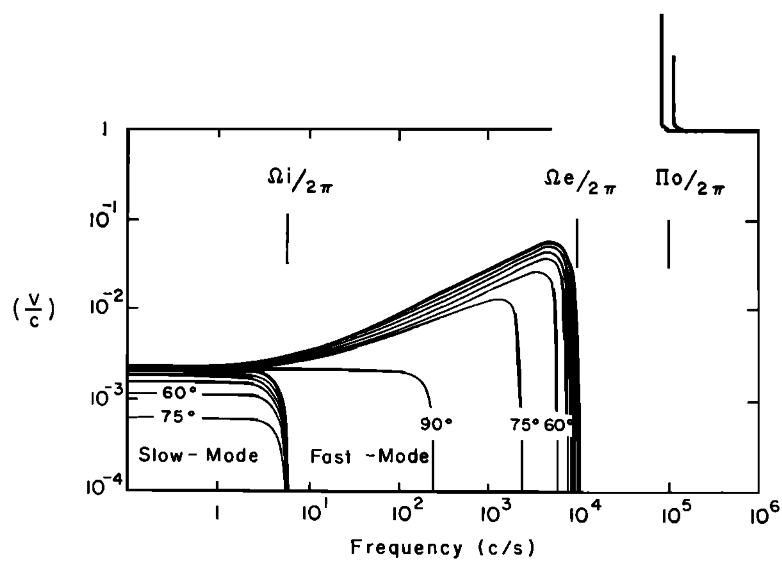

Fig. 2. Phase velocity profile of two magnetoionic waves; $\Pi_0/2\pi$ is the plasma frequency, $\Omega_e/2\pi$ the electron gyrofrequency, and $\Omega_i/2\pi$ the proton gyrofrequency.

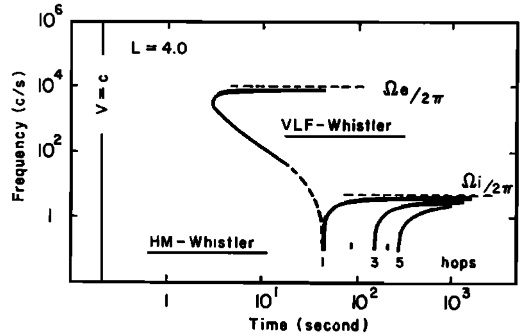

Fig. 3. A schematic pattern of the transit time of waves traveling along the geomagnetic field line ($\varphi_0 = 60°$).

The equation of a field line originating from the magnetic latitude φ_o at $r = a$ is

$$\frac{r}{a} = \frac{\cos^2 \varphi}{\cos^2 \varphi_0} = L \cdot \cos^2 \varphi \tag{4}$$

The dipolar representation of the geomagnetic field is used:

$$B = B_0 \sqrt{1 + 3 \sin^2 \varphi}(a/r)^3 \qquad B_0 = 0.31 \text{ gauss} \tag{5}$$

The proton density distribution in the magnetosphere is assumed to obey the inverse-cube law [*Smith,* 1961]:

$$n = n_0(a/r)^3 \tag{6}$$

and the value $n_o = 10^4/\text{cm}^3$ is tentatively adopted.

Then (2) is written as

$$\tau = \frac{4aL^{5/2}}{B_0/\sqrt{4\pi n_0 M}} \cdot \int_0^{\varphi_o} \cos^4 \varphi \frac{\left\{1 \pm \dfrac{\omega}{2\omega_c} \dfrac{\cos^6 \varphi}{\sqrt{1 + 3 \sin^2 \varphi}}\right\}}{\left\{1 \pm \dfrac{\omega}{\omega_c} \dfrac{\cos^6 \varphi}{\sqrt{1 + 3 \sin^2 \varphi}}\right\}^{3/2}} d\varphi \tag{7}$$

where ω_c is the ion gyrofrequency at the furthest point of the line of force ($\varphi = 0$, $r/a = L$). For the limiting case $\omega \ll \omega_c$, equation 7 recovers the known latitude-period relation of geomagnetic oscillations [*Obayashi,* 1958].

Computed results of the $\omega - \tau$ curves for geomagnetic latitudes $\varphi_o = 45°$, $60°$, and $65°$ are shown in Figure 4, and the theoretical frequency-time pattern of echoing sequence for the anisotropic waves is shown in Figure 5. The latitude variations of the minimum transit period ($\omega = 0$) and the cutoff frequency ($\omega_c/2\pi$) are shown in Figure 6.

These theoretical results are compared with the observed frequency-time displays of hm emissions. Since the observed repetition period and the emission frequency are of 1 to 5 minutes and of 0.2 to 5.0 cps, respectively, the hydromagnetic whistlers must originate somewhere between geomagnetic field lines $\varphi_o = 60°$ and $65°$, provided that the present proton-density distribution inferred from whistler data is an appropriate representation of the magnetosphere. Although most of the available data were observed at lower latitudes than those of the estimated source, there is considerable evidence that the hm emissions could propagate very long distances across the ionosphere or free space below [*Tepley,* 1964*a*, *b*]. Many important characteristics of hm emissions described earlier are all consistent with the result predicted by the present theory. It may be possible that hm emissions of a series of falling tones could be interpreted in terms of hydromagnetic waves of isotropic mode (the fast wave), being guided along the path of field-aligned ionization ducts. However, observational evidence is not sufficient to prove this possibility.

Origin of hydromagnetic whistlers. It has been demonstrated that hydromagnetic wave packets echoing between conjugate points along the geomagnetic field line can produce the observed frequency-time pattern of hm emissions. The problem remains, however, of exploring the mechanism of wave generation.

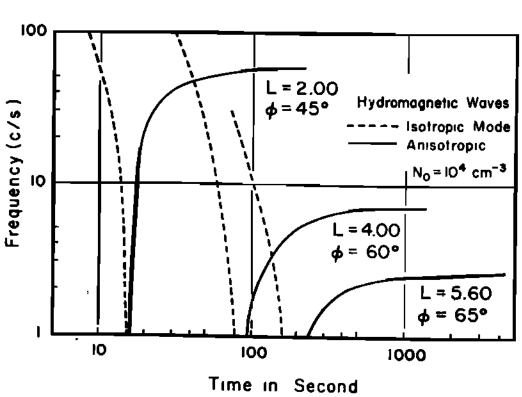

Fig. 4. Frequency versus transit time curves for the double-hop paths $L = 2.0$, 4.0, and 5.6.

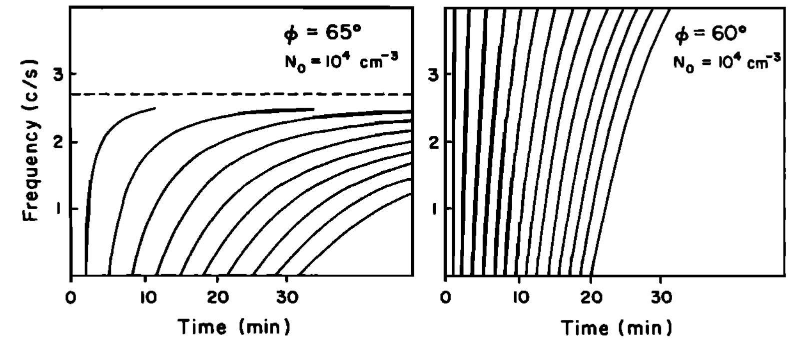

Fig. 5. Theoretical frequency-time displays of hydromagnetic whistlers for the paths L = 4.0 and 5.6.

There are at least two ways of generating hydromagnetic waves in the magnetosphere. The one is dynamical fluid motions at some boundary that are induced by a sudden intrusion of solar plasma clouds or by rapid wagging movements of the magnetospheric cavity surface. Consequently, resonant oscillations would be excited on the geomagnetic field lines. Their period is estimated to be of the order of a few minutes or more, and they have been identified as some of the long period micropulsations observed in the auroral zone [*Sugiura and Wilson*, 1964]. However, it is rather unlikely that this mechanism can provide the generation of very short period hydromagnetic oscillations because of the overwhelming inertia of the plasma motions involved. On the other hand, energetic particle beams may be capable of producing a variety of hydromagnetic emissions or of amplifying the waves through their unique interaction processes.

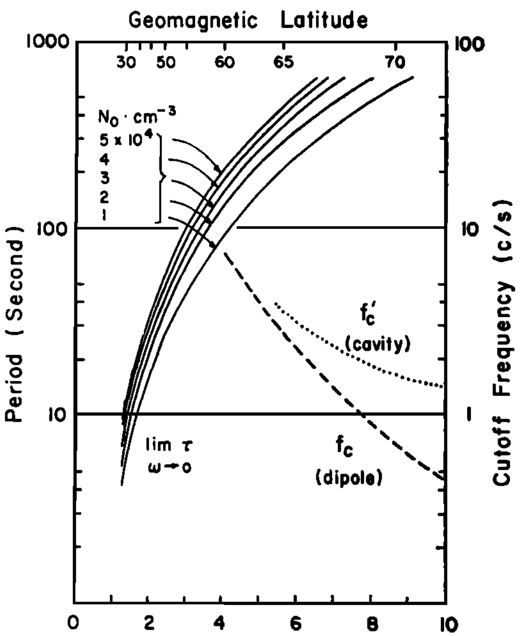

Fig. 6. Latitude variations of the minimum transit period ($\omega = 0$) and of the minimum proton gyrofrequency for respective geomagnetic field lines; f_c is the geomagnetic dipole field and f_c' the gyrofrequency at the equator for the geomagnetic field compressed within a spherical cavity of 10 earth radii.

Magnetobremsstrahlung. An accelerated charged particle moving in a magnetic field produces an emission whose radiation can match the wave mode in a plasma. In the general case in which a charge moves along the static magnetic field with a helical path, whose angular-gyrofrequency Ω (electron Ω_e, ion Ω_i) and its guiding center has a longitudinal velocity $u = v \cos \alpha$ and a transversal gyrating velocity $w = v \sin \alpha$, and for which the wave vector k makes an angle θ with the direction of the magnetic field, the radiated angular wave frequencies are determined from the conditions

$$\omega = s\Omega + ku \cos \theta \quad s = 0, \pm 1, \pm 2 \cdots \tag{8}$$

For the case $s = 0$, the relation is known as the Cerenkov condition, i.e.

$$u/V = 1/\cos \theta \tag{9}$$

where $V = \omega/k$ is the phase velocity of the wave. Cerenkov radiation is emitted in the forward direction with respect to the guiding center motion of the particle.

For the case $s \neq 0$, the radiation is due to the cyclotron harmonics $s\Omega$, and, in particular, when the particular speed exceeds the wave phase velocity, $u \cos \theta > V$, the anomalous cyclotron radiation arises, the one *Ginzburg* [1959] called 'superluminal particle radiation.' The frequency of an anomalously Doppler-shifted cyclotron radiation ($s < 0$), in the direction along the magnetic field, is obtained by the specified value of u/V_A, using the well-known dispersion relation in the anisotropic plasma [*Ginzburg*, 1961]:

$$\frac{u}{V_A} = \left(1 + |s| \frac{\Omega}{\omega}\right)\left\{\left(1 \pm \frac{\omega}{\Omega_i}\right)\left(1 \mp \frac{\omega}{\Omega_e}\right)\right\}^{1/2} \tag{10}$$

where the upper sign denotes the fast wave and the lower sign the slow wave. For the relativistic particle speed, $\beta = (v/c) \sim 1$, the angular-gyrofrequency $\Omega(1 - \beta^2)^{1/2}$ should be used. The excitation condition for the oblique waves at frequencies $\omega \ll \Omega_i$ is given by

$$\omega = |s| \, \Omega \sqrt{1 - \beta^2}/(u/V_A) \tag{11}$$

for the hydromagnetic slow wave propagating at any angle to the field except $\theta = 0$, where the radiation vanishes. For the hydromagnetic fast wave

$$\omega = \frac{|s| \, \Omega \sqrt{1 - \beta^2}}{(u \cos \theta / V_A)} \tag{12}$$

The radiation is emitted entirely into the forward hemisphere with respect to the direction of the moving particle, though the major part of the energy is radiated at an appreciably large angle from the field direction [*Liemohn*, 1964].

The normal Doppler-shifted cyclotron radiation ($s > 0$) is given by

$$\frac{u}{V_A} = \left(1 - |s| \frac{\Omega}{\omega}\right)\left\{\left(1 \pm \frac{\omega}{\Omega_i}\right)\left(1 \mp \frac{\omega}{\Omega_e}\right)\right\}^{1/2} \tag{13}$$

and the radiation is emitted in both forward and backward directions: however, the backward radiation only propagates in the frequency range $\omega \le \Omega_i$.

Wave and particle-beam interactions. The interaction between waves and particles moving through the plasma provides an important mechanism of energy transfer through their resonances and beam instabilities. Generally, there are two resonant conditions for the interaction between waves and plasma beams; the Doppler-shifted wave frequency seen by particles is either zero frequency or the particle gyrofrequency. The former requires that the beam velocity match the wave phase velocity in the direction of particle motion, which is essentially the Cerenkov condition given in the (9). This type of interaction is known as the longitudinal instability produced by the beam, viz., the coupling between the beam and longitudinal electrostatic plasma waves. However, there is no immediate coupling between the beam and transversal electromagnetic waves, though the plasma wave itself may be a growing mode [*Kimura*, 1961].

In the magnetoactive plasma the cyclotron resonance, which includes the effect of Doppler-shifted waves discussed earlier, is important. The plasma beam of a superluminal motion is capable of exciting waves whose amplitude increases rapidly. The excited wave propagates in the *same direction* as the beam, and its wave frequency is found by the resonance condition of the anomalous Doppler effect given in (10), (11), and (12). *Kimura* [1961] and *Neufeld and Wright* [1963] have shown that a large amplification of the transversal waves is possible through this mechanism by expending the energy of *longitudinal motion* of the plasma beam (the beam velocity in the direction of wave propagation), the coupling being provided by an *ion beam for the fast wave* and an *electron beam for the slow wave*. Under such conditions the plasma beam loses its stability, and particles generally become bunched and a coherent radiation is produced.

Another possibility of the growing wave interaction has been suggested by *Bell and Buneman* [1964] and Watanabe (private communication, 1964). A plasma beam traveling at appropriate velocity in the *opposite direction* to the wave propagation encounters the Doppler-shifted wave whose rotating field matches the particle gyrofrequency in the same sense: the *fast wave for electrons* and the *slow wave for ions*. This encounter results in the amplification of the wave, provided that particles in the beam initially have enough *transversal gyration velocities* so as to transfer their energy to the wave. The frequency for the excitation condition is the same as that for the normal Doppler effect given in (13), and an initial root-mean-square transversal particle velocity $\langle w^2 \rangle^{1/2}$ should be larger than the cyclotron velocity $|\Omega/k|$ in order that the growth of the wave exceed that of longitudinal plasma waves. It has also been shown that in this mechanism the magnetic field of the wave acts to shift the phase of particles so that their cyclotron radiation adds in phase in the backward direction [*Brice*, 1963].

For thermal particles of relatively low temperature, however, the resonance encounter usually results in a gain of the particle energy transferred from the wave. Consequently, the wave loses its energy, and this is known as the mechanism of the cyclotron damping or the Landau damping for transverse waves [*Scarf*, 1962*a*, *b*]. The wave propagating in the magnetosphere is attenuated by this mechanism even under the collisionless condition. For the hydromagnetic wave the damping effect becomes appreciable when the thermal velocity of protons $\langle u^2\rangle^{1/2}$ becomes comparable to $(\Omega_i - \omega)/k$, i.e.,

$$\langle u^2\rangle^{1/2} \simeq V_A\left(\frac{\Omega_i}{\omega}\right)\left(1 - \frac{\omega}{\Omega_i}\right)^{3/2} \qquad (14)$$

Source of hydromagnetic whistlers. The mechanism which is relevant to the generation of hydromagnetic whistlers may be a certain combination of the processes described above. An initiating wave may be produced by a spontaneous appearance of superluminal particles in the region near the top of a geomagnetic field line, where the phase velocity of a wave is minimum. On the geomagnetic field line of $\varphi_o = 65°$, the Alfvén velocity at the furthest point is about 500 km/sec according to the model used. The observed hm emission band in the auroral zone lies in the range between 0.1 and 0.5 cps, which corresponds to $\omega/\omega_o = 0.05 \sim 0.20$. The speed of protons required to generate such an emission will be 3000 ~ 10,000 km/sec, or about 50 ~ 500 kev, whereas the energy required for electrons is 10 Mev or more, which may not be unreasonable energy ranges as a sudden flash of particles could temporarily be trapped in the magnetosphere.

It may be argued that such a superluminal cyclotron radiation alone is sufficient to account for the observed emissions. The radiated power density of cyclotron emission from incoherent particles is given approximately by

$$I = \frac{2e^2}{3c}\,\Omega^2\left(\frac{v}{c}\right)^2\left(\frac{c}{V}\right)\cdot N \qquad (15)$$

The densities of 100-kev protons and of relativistic electrons being captured in the magnetosphere are $N_p \simeq 10^{-2}/\text{cm}^3$ and $N_e \leq 10^{-8}/\text{cm}^3$, respectively [*O'Brien*, 1964]. These yield the values which are certainly many orders of magnitude less than that of the observed hm emissions. It must be emphasized also that the superluminal particles alone cannot possibly produce a regular emission structure which has almost the same periodicity over many repetitive cycles.

Thus, a triggered wave packet, placed on the field line, must subsequently be amplified by any of the interaction mechanisms mentioned previously. It is necessary to have a stable coupling between the wave packet and the bunched plasma beam. However, since the kinetic energy of plasma beams is estimated to be much in excess of that required to account for the emissions, the wave need only set up the appropriate condition for an efficient conversion of particle kinetic energy to wave energy. A proton beam would be the source for a growing hydromagnetic wave (slow mode): the particles in the beam must have their transversal kinetic energy of about 100 kev and the longitudinal beam velocity must be 5000 ~ 10,000 km/sec. This beam velocity would be similar to that of $(\omega + \Omega_i)/k \simeq V$ for $\omega \gg \Omega_i$, i.e. near the phase velocity of VLF whistler waves (fast mode), and the beam may also be able to excite the VLF emissions simultaneously. Typical values of the growing time (*e*-hold amplitude) of excited waves are estimated to be of the order of a second (VLF wave) or less (hm wave), which may be sufficient to account for the observed growth rates of emissions. Therefore, it is suggested that so-called VLF pulsations are generated by the interaction between hydromagnetic whistlers and the high-speed proton beam.

According to the present theory, the frequency range of a wave may be limited by the available energy range of particles in the beam in the excitation mechanism. The deficiency of energetic protons of a sufficient flux above the 100-kev range causes the cutoff of waves below $\omega/\omega_o = 0.1$. If the particles in the beam spread in a certain energy band, the net emission can occur only if their velocity distribution is such that there are more particles in the beam at higher velocities than at lower velocities at a given range; i.e., the distribution must have a positive derivative that is highly nonthermal. This implies a possibility of having the emissions of very narrow band structures due to the complex velocity distribution of particles in the beam. However, for an over-all cutoff at the high frequency limit, it is tempting to attribute the cutoff to the absorption effect of waves due to the cyclotron resonance of thermal protons. According to the computation made by *Scarf* [1962], a significant sharp cutoff occurs at the frequency $\omega/\omega_c \simeq 0.6$ for temperatures of the order of 10^5 °K. This result suggests that the observed upper cutoff may well be explained by the present mechanism.

Discussions. Hydromagnetic emissions consisting of a series of over-lapping wavetrains of rising frequency are interpreted by hydromagnetic wave packets of anisotropic mode (Alfvén slow wave) propagating along the geomagnetic field lines. The rising frequency of emissions is attributed to the dispersive nature of the velocity of waves, and the repetitive period of the emission structure is associated with the transit time of the wave packet along the field-aligned path.

It has been shown that the structural characteristics of hm emissions are such that they originate mainly from the geomagnetic field lines whose L values range from 4 to 6, provided that a reasonable model of the magnetospheric particle density distribution has been used. Therefore, hm emissions received at the middle and low latitudes must be those that originated at high latitudes but propagated in or below the ionosphere. There is a possibility that a good ducting condition exists for hydromagnetic wave propagation in the ionosphere (100 ~ 1000 km), where the altitude profile of hydromagnetic wave velocity shows a steep trough. The observed evidence strongly supports the concept that hm emissions could propagate a considerable distance from high latitudes to the equator [*Tepley*, 1964*a*, *b*].

A generation mechanism of hydromagnetic whistlers has been proposed. A hydromagnetic wave packet may be triggered by a flash of high energy particles. The emission process invoked is anomalous cyclotron radiation [*Ginzburg*, 1961]. A spontaneous appearance of such high energy particles may be excepted at high latitudes, though the mechanism of rapid acceleration of particles has not been well understood. However, it is emphasized that the triggered radiation alone cannot be sufficient to account for the observed emissions.

Thus the triggered wave packet must, subsequently, be amplified by coupling with a plasma beam through the mechanism of cyclotron instabilities. As an energy source for the amplification, a proton beam whose streaming velocity is 5000 ~ 10,000 km/sec has been postulated. However, this may not exclude any other mechanism discussed here. Since these processes involve some nonlinear interactions, a further theoretical study is highly desirable.

The bandwidth of the hm emissions is related to the emission process as well as the propagation effect. The upper cutoff would be produced by the cyclotron resonance because of thermal protons (transverse Landau damping), while the lower cutoff is attributed to the upper limit of the speed of particles available in the beam with a sufficient flux. Some narrow band structures of emissions are suggestive of the existence of a complicated velocity distribution of particles in the plasma beam.

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